Indirect Search for Dark Matter

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INDIRECT SEARCH FOR DARK MATTER

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Possible dark matter candidates are reviewed as well as indirect search methods based on annihilation or decay channels of these particles. Neutralino is presently the best particle candidate and its annihilation produces high energy neutrinos, antiprotons, positrons and γ-rays. To date, only upper limits on neutrino fluxes from the center of the Earth or the Sun, were established by different experiments. Antiprotons detected by the BESS collaboration, if issued from the follow up hadronization of the annihilation process, exclude neutralino masses higher than 100 GeV. The EGRET γ-ray residual emission seen at high galactic latitudes above 1 GeV could be explained by neutralino annihilations if: i) the dark matter profile is "cored" and ii) the neutralino mass is $\leq$ 50 GeV. Sterile neutrinos in the keV mass range are a possible candidate to constitute warm dark matter. These particles may provide an adequate free streaming mass able to solve *some* difficulties present in the cold dark matter scenario at small scales and could also explain the natal kick of pulsars. MeV particles, dubbed *light* dark matter, proposed to explain the extended 511 keV line emission from the galactic center will also be discussed.

Title in Russian
Author(s) in Russian

Text of abstract in Russian

1. Introduction

Baryons represent only a minor percentage ($\sim$ 4%) in the matter-energy budget of the universe, the remaining and major part being probably under the form of some kind of "exotic" matter. Data on angular power spectrum of temperature fluctuations of the cosmic microwave background radiation derived from WMAP and on the luminosity-distance of type Ia supernovae [1,2,3], indicate that the "exotic" matter has in fact two components: one, which acts as a "repulsive" force, labeled *dark energy* and another, which is responsible for gravitational forces at large scales, dubbed *dark matter*. The former corresponds to about 70% whereas the latter corresponds to about 26% of the total matter-energy content of the universe. The dark energy component, sometimes identified as the "cosmological constant" (Λ) term, first introduced by Einstein, is responsible for the observed acceleration of the expansion of the universe [2,3]. Because of conceptual problems associated with the so-called "Λ"-term, different alternatives have been explored in the literature. The most popular, christened "quintessence", uses a scalar field ϕ with a suitable potential $V(\phi)$ so as to make the vacuum energy density vary with time. However, the possible nature of the dark energy will not be discussed in this paper, whose main purpose is to find answers to the question: *what is dark matter made of* ?

Among particles issued from the Standard Model, the only particle which has an important relic density is the neutrino. However, recent observational constraints obtained from WMAP data [1] imply that their total mass density should satisfy $\Omega_\nu h^2 < 0.0076$, considerably less than the amount of gravitational mass present in the universe ($\Omega_m h^2 = 0.13 \pm 0.02$). Moreover, neutrinos are relativistic at the freeze-out and due to their relativistic streaming, small-scale structures are erased, difficulting the formation of galaxies and ruling out neutrinos as an acceptable dark matter candidate.

Axions and massive Higgs-like bosons have also been proposed in the past as dark matter candidates. Presently, we do not know either the relic abundance or the interaction type besides gravitation to which these particles are subjected. Very massive boson fields may have played an important rôle in the formation of the present observed large structure of the universe, since they may experience gravitational instability [4]. Moreover, boson condensates could have been "seeds" of primordial black holes [5], which may grow by accreting dark and baryonic matter and are probably present today in the center of most of galaxies. One of the difficulties to form these bosonic configurations is that if there is no efficient cooling mechanism to get rid of the excess kinetic energy, the gravitational collapse leads to a diffuse virialized cloud, but not a compact object. This outstanding problem was considered in reference [6], where the authors showed that, in fact, there is a dissipationless cooling mechanism, similar to the violent relaxation of collisionless stellar systems, which leads to the formation of compact bosonic configurations. Lim-

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its on the density of these objects in the galactic halo were discussed in [5].

Proposed extensions of the Standard Model or Supersymmetric (SUSY) theories lead naturally to a series of candidates, which may be point-like or not. In the former case examples are sneutrinos, axinos, gravitinos, photinos, neutralinos, while in the latter, Q-balls are one interesting possibility [7,8], since their self-interaction cross section may be of the order of 20 mb or larger. These values are required for self-interacting dark matter halo models, in order to remove the central density cusp predicted by simulations, but not seen in the rotation curve of luminous galaxies [9]. Superheavy particles dubbed "cryptons", with masses around 10^{14-15} GeV, which could have been produced non-thermally in the very early universe, have also been proposed as a possible dark matter candidate [10]. If the decay timescale τ_X of "cryptons" is in the range $0.066 \leq \mathrm{H}_0\tau_X \leq 1.0$, then estimates of the relic density of these particles can be made. The reasoning is the following: high energy neutrinos can be produced by the decay of "cryptons". Non-zero mass very energetic neutrinos may annihilate interacting with cosmic background antineutrinos, producing Z^0 gauge bosons at the resonant energy $E_r = M_Z^2/2m_\nu$. If the neutrino mass is $m_\nu \sim 0.07$ eV, the resonant energy is $\sim 6 \times 10^{13}$ GeV. The Z^0 decay produces about 30% of very high energy protons and 70% of γ's. Since the flux of UHE protons are constrained by observations, the density of cryptons is restricted to the range $6\times10^{-10} < \Omega_X < 1.6\times10^{-6}$ [5], several orders of magnitude less than the value derived from WMAP data [1].

Presently, the most plausible SUSY dark matter candidate is the neutralino (χ), which is the lightest supersymmetric particle. The neutralino is stable and hence is a candidate relic from the Big Bang, if R-parity quantum number, introduced to avoid a too rapid proton decay, is conserved as is the case in the Minimal Supersymmetric Extension of the Standard Model (MSSM). The neutralino is an electrically neutral Majorana fermion whose mass m_χ can range from a few GeV to few hundreds of TeV. A lower limit of about 30 GeV has been set by the LEP accelerator [11], while an upper limit of 340 TeV is favored theoretically to preserve unitarity [12].

2. Neutralino detection

2.1. Direct methods

Direct detection of dark matter particles is based on the possibility of measuring the recoil energy (few up to few tens of keV) of a nucleon after an elastic collision with a putative WIMP. Since the interaction cross section is quite small ($< 10^{-6}$ pb), large detector masses are required in order to obtain a significant event rate. The expected low event rate demands a very low radioactive and cosmic ray background, which is one of the major difficulties of a direct search for dark matter particles (see reference [13] for a recent review on direct experiments). Direct detection experiments also use the annual modulation of the signal due to the orbital motion of the Earth around the Sun as a signature. It should be emphasized that the search strategy and data analysis depend on the *assumed* spatial distribution of dark matter and its dynamics in the galactic halo, which are not well understood yet. For instance, it is not established if dark matter halos are presently relaxed structures or not. Whether dark matter is homogeneously distributed with isotropic velocity distribution or whether there are local inhomogeneities such as local streams, e.g., like that manifested through the tidal arms of the Sagittarius dwarf, is not entirely clear. Moreover, dark halos are generally not at rest and have considerable angular momentum [14], whose vector direction is generally not coincident with that of the present spin axes of baryonic disks [15]. All of these are just a few of many uncertainties about properties of dark halos which overshadow the interpretation of direct experiments.

2.2. Indirect dark matter searches

Indirect methods search for products of self-annihilation of neutralinos such as energetic leptons, hadrons and particles emerging in the follow up hadronization and fragmentation processes, according to the channels:

$$\chi\bar{\chi} \rightarrow l\bar{l}, q\bar{q}, W^+W^-, Z^0Z^0, H^0H^0, Z^0H^0, W^{\pm}H^{\mp} \quad (1)$$

High energy neutrinos are produced either in quark jets ($b\bar{b}$ interactions) or in the decay of τ leptons and gauge bosons. Neutrinos produced in the former process are less energetic than those produced in the latter. Neutralinos can be decelerated by scattering off nuclei and then accumulating at the center of the Earth and/or at the center of the Sun (or inside any other gravitational potential well), thus increasing the annihilation rate.

Searches for neutrinos resulting from the above processes in the center of the Earth have been performed by different experiments as MACRO [16], Baksan [17], Super-Kamiokande [18] and AMANDA [19,20]. So far, these experiments have only managed to set upper limits on neutrino fluxes coming from the center of the Earth or from the Sun. However, many uncertainties still exist in estimates of the capture rate of WIMPs by the Earth. New detailed numerical simulations of the diffusion process suffered by WIMps inside the solar system indicate that the velocity distribution is significantly suppressed below 70 km/s [21] (and references therein). As a consequence, the capture and the annihilation rates are substantially reduced if the WIMP mass is higher than $\sim$ 100 GeV. This suppression will make the detection of neutrinos resulting from the annihilation of neutralinos in the center of the Earth much harder when compared with previous estimates [21].

Besides high energy neutrinos, antiprotons [22,23] and positrons [24,25] are produced in the annihilation process too. Antiprotons are the consequence of the hadronization of quarks and gluons whereas positrons are mainly the result of the decay of charged gauge bosons.

Antiprotons (and positrons) are also expected to be generated by interactions of cosmic rays with interstellar matter. However, the energy spectrum of secondary antiprotons falls steeply for energies less than a few GeV, which could favor the distinction between production by cosmic ray interactions and neutralino annihilation. Antiprotons with energies in the range 0.18-1.4 GeV were detected by the balloon borne experiment BESS [26]. Uncertainties on the parameters characterizing our diffusive halo (scale of the confinement region, dependence of the diffusion coefficient on energy, etc.) difficult analyses of such data. In spite of these unsolved problems, the present data seem to exclude neutralino masses higher than 100 GeV [23]. Concerning cosmic positrons, data obtained by the High-Energy Antimatter Telescope (HEAT)[27] suggest a slight flux excess above 5 GeV. It was shown that such an excess cannot be explained by annihilation of dark matter particles, unless a substantial number of substructures are present in the galactic halo at a rather unlikely amount [28].

Energetic γ-rays are also produced during the neutralino annihilation process. Since this is one of the most interesting possibilities for indirect detection of supersymmetric matter, we will analyze this aspect in some more detail in the next section.

3. γ-rays from dark halos

The decay of neutral pions formed in the hadronization process is the dominant source of continuum γ-rays. Besides the continuum emission, two annihilation channels may produce γ-ray lines. The first is $\chi\bar{\chi} \rightarrow \gamma\gamma$, where the photon energy is $\sim m_\chi$ and the second is $\chi\bar{\chi} \rightarrow Z^0\gamma$, where the photon energy satisfies $\varepsilon_\gamma = (m_\chi - m_Z^2/4m_\chi)$. The latter process is only important if the neutralino mass is higher than $\sim$ 45 GeV.

The prediction of γ-ray fluxes require two independent inputs: that coming from particle physics for issues such as the interaction cross section and the number of photons per annihilation, and the input from astrophysics for problems such as the spatial distribution of dark matter in potential sources.

Here we present some results and predictions based on our previous work [29]. For the sake of completeness, we summarize here the main assumptions of these calculations (the reader is referred to [29] for more details): a) neutralinos are initially supposed to be in thermal equilibrium with the cosmic plasma; b) they are non-relativistic at decoupling and their relative abundance at the freezing point should provide a relic density, corresponding to $\Omega_m \approx 0.26$; c) the number of photons per annihilation is estimated from fragmentation functions of QCD jets of energy $\sim m_\chi$. Under these simplified conditions, the neutralino mass is the sole free parameter. For masses in the range $10 \leq m_\chi \leq 2000$ GeV, the decoupling temperature varies within the interval 0.4 - 70 GeV and the thermally averaged annihilation reaction rate $< \sigma_{\chi\bar{\chi}} v >$ varies very little, namely, (7.7 - 9.5)$\times 10^{-27}\, cm^3 s^{-1}$, if the "s-wave" term only is considered.

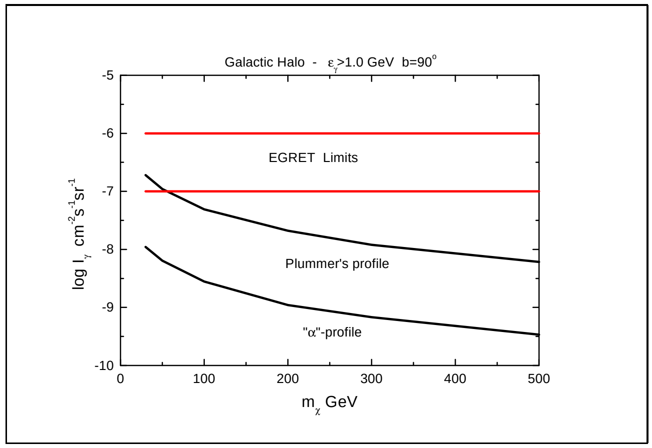

Figure 1: Predicted γ-ray intensity above 1 GeV ($\mid b \mid = 90^o$) as a function of the neutralino mass and for two density profiles. EGRET limits are also given.

The galactic center is a privileged potential source of γ-rays due to its proximity and high column density. However, the γ-ray emission from this direction is highly contaminated by the local background, mostly produced by cosmic ray interactions with the interstellar environment. In the energy range 0.1 - 1.0 GeV, cosmic ray electrons produce high-energy photons either by inverse Compton scattering or bremsstrahlung, while the proton component produces γ-photons via the decay of neutral pions generated in collisions with interstellar matter.

EGRET data analyses suggest that, at high galactic latitudes, there is a residual intensity of $10^{-7} - 10^{-6}$ ph cm$^{-2} s^{-1} sr^{-1}$ above 1 GeV, even after correction for the expected background of cosmic rays and the diffuse extragalactic emission [30]. The expected γ-ray intensity for energies above 1 GeV at $\mid b \mid = 90^o$ as a function of the neutralino mass is shown in fig. 1.

The expected γ-ray intensity is calculated from the equation

$$I_\gamma(r_p) = \frac{< \sigma_{\chi\bar{\chi}} v >}{4\pi m_\chi^2} Q_\gamma \mathcal{I}(r_p) \qquad (2)$$

In the above equation, Q_γ is the number of photons produced per annihilation with energies higher than a given value [29] and $\mathcal{I}(r_p)$ is the *reduced intensity* at a given projected distance r_p from the center, defined as

$$\mathcal{I}(r_p) = \int \rho_\chi^2(\sqrt{s^2 + r_p^2})ds \quad (3)$$

and the integral should be performed along the line of sight.

Two density profiles were considered in the calculations. The first, the recently proposed "α"-profile [31], which provides a *finite* central density and is able to fit adequately the inner structure of dark halos resulting from numerical simulations, namely,

$$\rho(r) = \rho_* exp\{-\frac{2}{\alpha}[(\frac{r}{r_*})^\alpha - 1]\} \quad (4)$$

The second is a Plummer profile, intended to represent better the baryon-to-dark matter ratio resulting from analyses of rotation curves of bright galaxies, e.g.,

$$\rho(r) = \frac{\rho_0}{[1 + (1/3)(r/r_0)^2]^{5/2}} \quad (5)$$

For the Galaxy, the parameters defining the aforementioned density profiles are: $\rho_* = 0.0061\, M_\odot pc^{-3}$, $r_* = 11.6$ kpc, $\alpha = 0.17$ ("α"-profile) and $\rho_0 = 0.038\, M_\odot pc^{-3}$, $r_0 = 12.2$ kpc (Plummer profile) [29].

Inspection of fig. 1 shows that the EGRET residual emission can be explained if the neutralino mass is less than 50 GeV, a value marginally consistent with the LEP lower limit. Contrary to what is generally obtained when the galactic center direction is considered, at high latitudes the Plummer profile predicts an intensity *higher* than that derived from a "cuspy" density profile. This is easily understood since the latter profile gives a larger mass concentration near the center while the former has a shallower mass distribution. At high galactic latitudes, the predicted intensities from the "α"-profile are always below the EGRET residual values. In this case, an important enhancement by substructures in the halo is required. However, the expected enhancement factor, according to numerical simulations performed by [29], is rather small, not exceeding a factor of 2. Presently, a firm conclusion cannot be made since the EGRET residuals are in the sensibility limit of the instrument. The situation is expected to improve greatly with the forthcoming Gamma-ray Large-Area Space Telescope (GLAST).

The study of γ-ray emission with GLAST has some advantages over atmospheric Cherenkov telescopes: i) lower energy threshold, allowing to probe neutralino masses above 10 GeV; ii) the background is mainly due to the diffuse extragalactic emission, and iii) the spatial resolution varies with the threshold energy, permitting us to probe also the density profile.

Here we consider two energy thresholds: 0.1 and 1.0 GeV. Then, we compare the predicted γ-ray intensities for M31 and M87 as a function of the neutralino mass with the detectability limit of GLAST. Parameters defining the halo properties of these galaxies are the same as [29]. Both objects have probably a massive black hole in their centers [32], which boost significantly the γ-emission by producing a central density spike within their sphere of influence. This effect was included when γ-ray fluxes were computed.

Table 1: Neutralino masses from positive or negative detection of M31 and M87 by GLAST

Object	$E_\gamma > 0.1$ GeV	$E_\gamma > 1.0$ GeV	profile	m_χ (GeV)
M31	no	no	cored	> 20
M31	yes	yes	cuspy	< 300
M31	yes	no	cored	< 20
M31	no	yes	cuspy	300-500
M87	no	no	cored	> 100
M87	yes	yes	cuspy	< 60
M87	yes	no	cored	-
M87	no	yes	cuspy	60-100

The result of combining the information on both aforementioned energy thresholds is summarized in table 1. Columns two and three indicate if the galaxy is detected or not at the corresponding energy threshold and consequences for the expected density profile (column four): "cored" or "cuspy". Finally, column five gives the neutralino mass range expected from a positive or negative detection by GLAST.

4. Warm dark matter...?

Presently, the cold dark matter paradigm explains successfully the large-scale structure in the galaxy distribution on scales of $0.02 < k < 0.15$h Mpc^{-1} [33,34]. The dark matter power spectrum on these scales derived from large redshif surveys as, for instance, the Anglo-Australian 2-degree Field Galaxy Redshift Survey (2dF-GRS), is also consistent with the Lyman-α forest data in the redshift range $2 < z < 4$ [35,36,37].

In spite of these impressive successes, there are still discrepancies between simulations and observations at scales ≤ 1 Mpc. The first problem concerns the sharp central density cusp of dark matter halos predicted by simulations and not seen in the rotation curves of bright spiral galaxies [38,39]. The second difficulty is related to the large number of sub-halos present in simulations but not observed [40,41], as in the case of our Galaxy or M31. Besides these difficulties, deep surveys ($z \geq 1-2$) as the Las Campanas Infrared Survey, HST Deep Field North and Gemini Deep Deep Survey (GDDS) are revealing an excess of massive galaxies with respect to predictions of the hierarchical scenario [42].

These problems could be alleviated if dark matter particles had a free streaming (or Landau damping) length-scale higher than usually supposed. In this case, the smearing out of the small scale structure could bring simulations in better agreement with observations, solving some of the difficulties mentioned above [43]. Particles decoupling relativistically but having became non-relativistic *before* the matter-radiation equality, constitutes the so-called "warm" dark matter. These particles have a velocity dispersion higher than neutralinos when structures began to be formed, thus filtering density perturbations at a higher cut-off.

Sterile neutrinos are a possible "warm" dark matter particle candidate [44]. These particles are Standard Model singlet fermions, which couple to the conventional ("active") neutrinos ($\nu_e \nu_\mu \nu_\tau$) solely via effective mass terms and are neutral under all Standard Model gauge forces. Very massive sterile neutrinos arise naturally in the so-called "see-saw" models in Grand Unified Theories (GUTs) [45].

Besides their interest for cosmology, sterile neutrinos have been proposed to solve the apparent discrepancies between the neutrino mass-squared differences (δm_ν^2) resulting from several experiments and now explained simply in terms of oscillations among the three active neutrinos [46]. The conversion of active into sterile neutrinos has also been invoked to solve "anemic" r-process nucleosynthesis in supernova ejecta, resulting from neutrino-driven shocks. Such a conversion reduces the electron number per baryon Y_e, favoring the nucleosynthesis of heavy (and neutron rich) elements [47].

In order to be an acceptable dark matter candidate, sterile neutrinos must satisfy some requirements: i) they must be able to produce the observed relic density; ii) their abundance should not alter the results of big-bang nucleosynthesis; iii) they should obey the constraints imposed by the core collapse of SN1987A and, finally, iv) have a lifetime longer than H_0^{-1}. Some of these requirements have recently been reviewed in [48].

Taking into account different constraints, it is possible to define a region relevant for cosmology in the plane "mass-mixing angle" (Fig. 2). Based on calculations performed by [49], curves 1 and 2 define respectively the region where these parameters satisfy the condition $\Omega_m h_0^2 = 0.11$ and the region disfavored by considerations on the supernova core collapse. The resulting density of sterile neutrinos (curve 1) was estimated from non-equilibrium processes in the early universe, taking into account incoherent resonant and non-resonant scattering and an initial lepton asymmetry $L_\nu = 0.01$ [49].

Sterile neutrinos, if they do not feel Standard Model gauge interactions only, are labeled "weakly sterile" whereas if they do not feel *any* gauge interaction (including those beyond the Standard Model), they are dubbed "fully sterile". In the former case, they can decay into lighter "active" neutrinos or radiatively, with a decay branch ratio $\Gamma(\nu_s \to \nu_a \gamma)/\Gamma(\nu_s \to 3\nu_a) = 27\alpha/8\pi$, the photon energy satisfying $\epsilon_\gamma \sim \frac{1}{2} m_{\nu_s}$. This X-ray line emission can be considered as a possible signature of keV-sterile neutrinos. Curve 3 in fig. 2 results from the assumption that in a typical cluster of galaxies

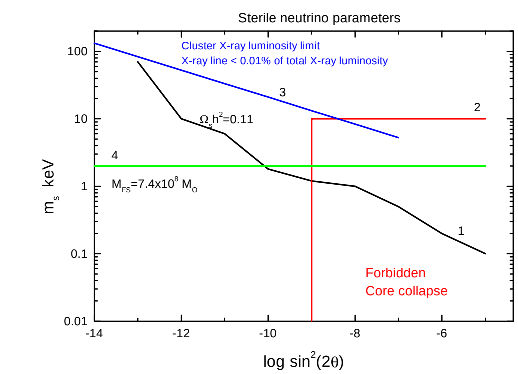

Figure 2: Allowed masses and mixing angles for sterile neutrinos

of mass of about $10^{14} M_\odot$, the X-ray line flux produced by the decay of sterile neutrinos is of the order of 10^{-4} of the continuum emission due to the hot gas. Finally, curve 4 indicates the "free-streaming" mass ($M_{FS} = 7.4 \times 10^8 M_\odot$) for a 2 keV sterile neutrino. Lower sterile neutrino masses will excessively increase M_{FS}, destroying the agreement between theory and observations at large scales. According to fig. 2, masses up to 10-20 keV are still allowed, but then the M_{FS} scale is so low that practically no differences from cold particle dynamics exist.

It is worth mentioning that sterile neutrinos in the mass range 1-20 keV and with comparable mixing angles could also be able to explain the origin of the natal kick of pulsars [50], which could be an additional point in favor of their existence.

5. ... or Light dark matter ?

Recent observations with the spectrometer SPI on board of the space observatory INTEGRAL have not only confirmed past detections of the 511 keV line emission from the galactic center, but have also revealed the extended nature of the emission [51]. This emission is the indisputable signature of electron-positron pair annihilations. Possible astrophysical sources of positrons as neutron stars, black holes, novae, type Ia supernovae fall short of explaining the measured line intensity ($9.9 \times 10^{-4}\, cm^{-2} s^{-1}$). Positrons can be generated in the neutralino annihilation process through different channels (see eq. 1). In particular, charged and neutral pions, produced roughly at the same number, will decay ultimately into e^+, e^- and photons respectively. Thus, if positrons in the galactic center are originated from $\chi\bar{\chi}$ annihilations, a γ-ray flux ($\epsilon_\gamma > 60$ MeV) *higher* than EGRET upper limits would have been observed, which is not the case. As a consequence, several alternative scenarios involving either annihilation or decaying dark matter particles have been proposed to explain the 511 keV emission.

Decaying axinos, with masses in the range 1-300 MeV, in an R-parity violating model of supersymmetry could be possible candidates, producing positrons through the channels, $\tilde{a} \rightarrow \nu_\tau e^+e^-$ or $\tilde{a} \rightarrow \nu_\mu e^+e^-$ [52]. In this scenario, axinos constitute the major dark matter component and might be present in the galactic halo with a cusped density profile such as $dlg\rho/dlgr \sim 1.2$.

Weakly sterile neutrinos were also proposed as a source for positrons by means of the decay channel $\nu_s \rightarrow \nu_a e^+e^-$ [53]. In this case, masses of the sterile neutrino are in the range 1-50 MeV. A negative aspect of this scenario is that the required mixing angles consistent with the desired mass interval lead to cosmic densities of $\Omega_{\nu_s}h^2 \sim 10^{-6}$. Thus, it is not possible to explain simultaneously the 511 keV emission *and* the cosmic dark matter density.

A rather different approach was followed in [54]. New 0-spin MeV relic particles are postulated, feeling a force field carried by a new light gauge boson U. Positrons would be generated almost at rest via annihilation, e.g., $X\bar{X} \rightarrow e^+e^-$. If the annihilation cross section is velocity dependent and if the density profile of the galactic halo have a central slope $dlg\rho/dlgr \sim 0.6$, then it is possible to explain the observed spatial profile of the 511 keV line emission and to obtain a concentration consistent with the relic dark matter density [55,56].

MeV thermal relic particles are expected to be coupled to the cosmic plasma at the epoch of big-bang nucleosynthesis and thus, they might contribute to the energy density and expansion rate. If, during nucleosynthesis, X-particles are mainly coupled to neutrinos, then their masses should be *higher* than 10 MeV in order not to alter the predicted abundances of ^{2}H, ^{4}He and ^{7}Li. If the coupling is essentially electromagnetic, X-particles in the mass range 4-10 MeV can even improve slightly the agreement between predicted and observed abundances [57].

Mass limits for dark matter particles can also be obtained from the power spectrum of primordial fluctuations at small scales ($< 1h^{-1}$ Mpc) derived from Lyman-α absorbers present in the spectra of quasars [58]. However, these limits depend on the adopted reionization epoch. Data on high-redshift quasars suggest that reionization occurred at $z \sim 6$, implying dark matter particles with masses around 1-5 keV [59], whereas WMAP data favor an earlier epoch ($z \sim 20$), implying particle masses $\geq$ 1 MeV [1,58]

6. Conclusions

New EROS data combined with previous microlensing observations were analyzed in [60], leading to an upper limit of about 10% for MACHOs in the mass range $10^{-6} - 0.3\,M_\odot$, able to contribute to the total mass of the galactic halo. This result suggests that most of the halo dark matter must probably be under the form of elementary particles.

Supersymmetric particles are privileged candidates. Several experiments are underway for the direct detection of WIMP particles. Up today, only the DAMA collaboration claims for a positive detection of a modulated signal compatible with a particle mass of 52 ± 10 GeV and a WIMP-nucleon cross section of about 7×10^{-6} picobarn. No satisfactory explanations have been found to explain the nature of such a signal face to negative results of other experiments [61].

Searches for energetic neutrinos resulting from neutralino annihilations in the center of the Earth or in the center of the Sun impose only upper limits on the fluxes. The comparison of these limits with theoretical expectations is still quite doubtful, since uncertainties present in the calculations of the capture rate of WIMPs by the Earth were not completely removed yet [21]. Antiprotons in the energy range 0.18-1.4 GeV detected by BESS collaboration, if produced in the follow up hadronization of neutralino annihilations, imply masses $m_\chi < 100$ GeV.

γ-rays resulting from π^o decay, formed in the hadronization process, are a promising possibility of indirect detection of dark matter. Searches for very high energy photons via atmospheric Cherenkov telescopes such as VERITAS, CELESTE, MAGIC, have not revealed any positive signal yet. The quite uncertain EGRET residual emission seen at high galactic latitudes above 1 GeV could be explained by neutralino annihilations if: i) the dark matter profile is "cored" and ii) the neutralino mass is $\leq$ 50 GeV. Notice that this mass limit is compatible with those derived from antiproton data analysis and from LEP data. Detection or upper limits on γ-ray fluxes from potential sources as M31 or M87, at different energy thresholds by the forthcoming GLAST, will improve considerably limits on the neutralino mass and will shed some light on the their spatial distribution inside galactic halos.

Difficulties with *cold* dark matter at small scales lead to alternative scenarios as *warm* particles, whose a possible candidate is a sterile neutrino in the keV mass range. These particles provide an adequate free streaming mass able to solve *some* small scale problems and are not in conflict with X-ray data from galaxy clusters. Moreover, they provide also a natural mechanism to explain the natal kick of pulsars. However, structures in a warm dark matter universe appear lately in comparison with a cold dark matter model, being a difficulty to form early sources responsible for the reionization of the universe evidenced by WMAP.

Finally, the extended nature of the 511 keV line emission from the galactic center revealed by INTEGRAL observations, raised the possibility of the existence of MeV dark matter particles, feeling a new gauge force field. These particles will not affect the primordial nucleosynthesis but, from a dynamical point of view, they will have the same difficulties at small scales as heavy particles.

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